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A VERY STABLE AND LINEAR 10-GAIN DIRECT CURRENT AMPLIFIER

BY

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November 1964

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SUMMARY

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This paper presents the design of an amplifier which increased the dynamic range of a photomultiplier detector signal channel by a factor of 10. The linearity and stability of the 10-gain amplifier make it unique for the application of low-level signal amplification in conjunction with an electrometer amplifier.

It is well to note that the amplifier has been qualified under the environmental conditions experienced by an Aerobee rocket payload during lift-off and operation in space.

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INTRODUCTION

Direct current amplifier circuitry techniques were generally used in designing this amplifier. These methods have been described in the engineering literature (References 1 and 2) and therefore will not be discussed in great detail. The intent here is to present the amplifier circuitry and to discuss the basic considerations that led to the design.

Aerobee rockets are instrumented to obtain stellar spectra in the ultraviolet from above the atmosphere (Reference 3). To cover the expected range of stellar intensities, it is necessary that the amplifiers used with the detector photomultipliers in the instrumentation payload have as wide a dynamic range as possible. However, the detector signal amplifiers can only provide a dynamic range which, in effect, represents the desired range of star intensities, within the voltage limits imposed by the rocket telemetry system. The telemetry used in an Aerobee rocket has a linear response from 0 to 5 volts, and the received signal as recorded on a strip chart can be read to an approximate accuracy of ±0.025 volt.

To extend the dynamic range of the system and still maintain the required high accuracies, a 10-gain amplifier was designed to be added to the existing electrometer amplifier (Reference 4).

In the detector signal channel, the electrometer amplifier follows the detector photomultiplier and serves to amplify the current output from the photomultiplier tube. The output signal from the electrometer amplifier is from 0 to 5 volts and is fed to a telemetry channel and to the input of the 10-gain amplifier.

The 10-gain amplifier operates only on a portion of the electrometer signal output, namely, over a 0- to 0.5-volt range. The signal output from the 10-gain amplifier also is connected to a telemetry channel. Here again, the usable voltage range is 0 to 5 volts. Figure 1 shows the increase in dynamic range accomplished, with equivalent accuracy, by use of a 10-gain amplifier. The detector output signal (electrometer input signal) is proportional to the stellar ultraviolet signal input to the detector.

In effect, the two amplifiers provide two independent outputs (after amplification from one photomultiplier input) which differ by a factor of 10 in sensitivity.

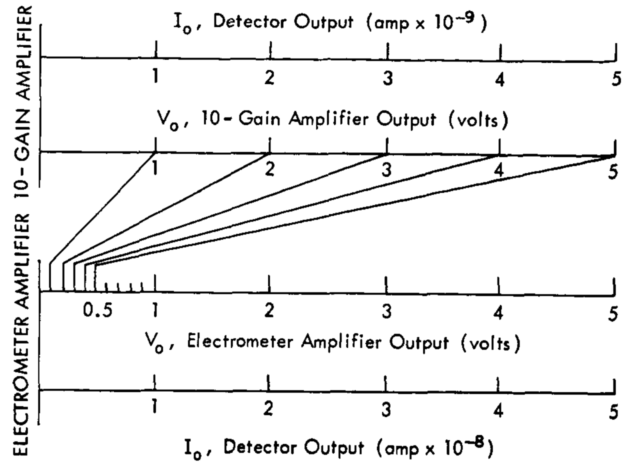

Figure 1—Comparison of dynamic range accomplished with the 10-gain amplifier versus the electrometer amplifier.

SPECIFICATIONS

The specifications for the amplifier are as follows:

Voltage gain: 10 ± 1%

Temperature range: +10° to +40°C

Input: 0.0 to 0.5 volt

Output: 0.0 to +5.0 volts

Linearity variation: ±0.03%

Maximum output: +7 volts

Bandwidth (minimum): dc to 100 cps

Output load impedance: 100 kilohms (minimum)

Input source impedance: 400 ohms (approx.)

Available supply voltage: ±16 volts

The noise level was not considered a problem, since this amplifier was preceded by an electrometer amplifier with a relatively high gain.

No limit was placed on the allowable power; however, in rocket instrumentation weight is at a premium, and the power should of course be minimal. This was a prime consideration in the design of the 10-gain amplifier.

CIRCUIT DESIGN

To obtain light weight, small size, reliability, low power dissipation, and the ability to operate from existing power sources, a transistor amplifier was chosen as the best means of meeting the specification requirements.

To obtain the correct voltage phase with the minimum number of transistor stages, an n-p-n and a p-n-p transistor were used in the two-stage configuration shown in Figure 2.

With the correct voltage phase established, the next question was: Could a two-stage transistor amplifier furnish the required current gain? A simple calculation can be made:

The source impedance to the amplifier is the output of the electrometer amplifier, which is approximately 400 ohms. To minimize loading, the input to the 10-gain amplifier was set at 5000 ohms – approximately a factor of 10 greater:

$$Z_{in} = 5.0 \text{ kilohms} .$$

Then the input signal current is

$$I_{in}(\text{max.}) = \frac{V_{in}(\text{max.})}{Z_{in}} = \frac{0.5 \text{ volt}}{5 \text{ kilohms}} = 0.1 \text{ ma} .$$

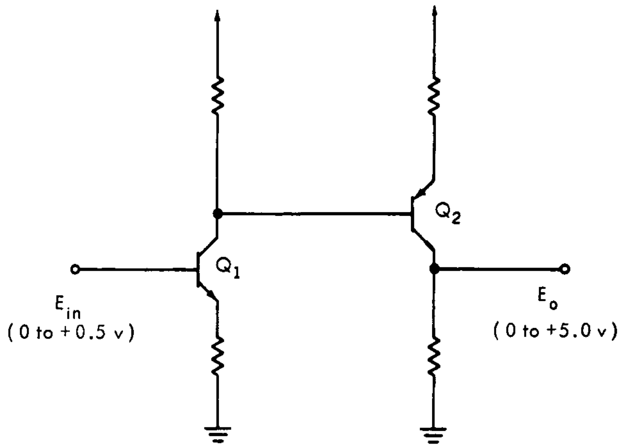

Figure 2—Basic amplifier design.

Although the actual telemetry load impedance is 100 kilohms minimum, Z_o was chosen to be only 5 kilohms to lessen the effect of the telemetry load on the amplifier and yet still provide a voltage gain.

The output signal current is

$$I_o = \frac{V_o(\text{max.})}{Z_o} = \frac{5 \text{ volts}}{5 \text{ kilohms}} = 1 \text{ ma} .$$

Then the current gain B required per amplifier is

$$B_{amp} = \frac{I_o}{I_{in}} = \frac{1 \text{ ma}}{0.1 \text{ ma}} = 10 .$$

Also,

$$B_{amp} = B_1 B_2 ,$$

where B_1 and B_2 represent the current gain for the first and second stages, respectively.

Considering the gain for each stage to be equal, the current gain required per stage is

$$B_{stage} = \sqrt{B_{amp}} = 3.33 .$$

This gain can be achieved easily with the lower gain type of transistors which offer an approximate minimum current gain of 10; therefore, in designing for a required current gain per stage of 3.33, considerable loading can be tolerated by stabilizing networks while still achieving the required overall current gain of 10. Note that the required current gain, with the load impedances considered, has the same value as the required voltage gain.

First-Stage Design

It is desirable to operate a common emitter stage at near-zero base resistance; but, because of the isolation required between the two amplifiers, this could not easily be done. It was felt that stability could be gained by using a large swamping resistor in the emitter of the first stage and negative feedback from the collector to base. This is shown schematically in Figure 3.

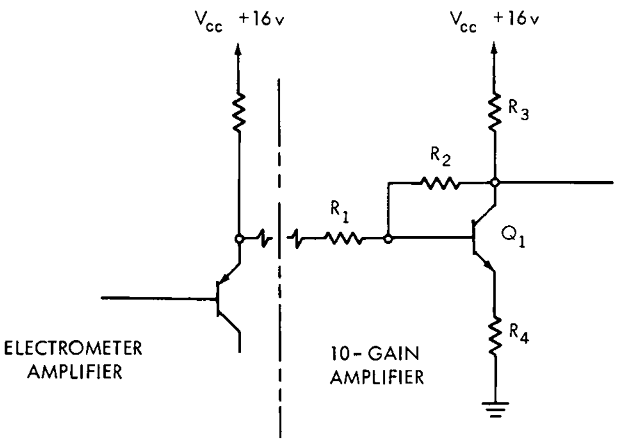

Figure 3—First-stage compensation.

The emitter resistance R_4 was chosen at 1 kilohm to swamp out the temperature-dependent effects of the base-to-emitter diode junction (Reference 5). The collector load resistance R_3 was then chosen to establish a load line which will give good linearity in the output for the expected base current swing while keeping in mind that the voltage drop across R_3 has to be sufficient to drive the next stage. Actually, in a dc amplifier where more than one stage is involved, the interactions from the loading, voltage, and current effects of the various stages are difficult to calculate. However, where these effects are small, approximations can be made.

The stage isolation resistance R_1 was adjusted to maintain a voltage input to the base of Q_1 slightly above the threshold voltage of the base emitter junction of Q_1. Then R_2, the feedback resistor, was calculated from the following relation:

$$R_2 = \frac{S_I V_{cc}}{I_E} ,$$

where S_I is the current stability factor (Reference 1, pp. 52-59) derived from the transistor curves for the expected temperature range and allowable variation in I_E.

Second-Stage Design

The design of the second stage follows considerations similar to the design used for the first stage. The second stage is shown in the composite design of Figure 4.

For correction of nonlinearity and for stabilization of the second stage, a sensistor is used in the emitter of the second stage. A potentiometer was added for "zero level" output voltage adjustment and the zener diode to limit the output voltage. The requirement here was to prevent the output from exceeding 7 volts while still maintaining a 0- to 5-volt linear range. To maintain the output at zero volts for no signal input, it was necessary to tie the collector load resistor of Q_2 to a negative potential.

During conduction of D_1, the resistance R_{10} acts to limit the current through Q_2 and through the sensistor R_9, which is a temperature-sensitive device with a relatively long time constant. Large signal amplitudes above the zener breakdown voltage of D_1 now can be tolerated without causing a change in the operating characteristics of the amplifier. Figure 4 shows the completed amplifier circuit.

All the Figure 4 resistors and the sensistor are rated at 1/4 watt and, in most cases, are of the indicated value. It was not necessary to "pick" the transistors for similar characteristics. Only rarely was it necessary to change the resistors to maintain good linearity, gain, and temperature stabilization. The changes, if required, are as follows:

1. For exactly a gain of 10, select R_4 between 1.3 and 1.8 kilohms.

2. To alter the range of the zero-adjust potentiometer, select R_5 between 27 and 51 kilohms.

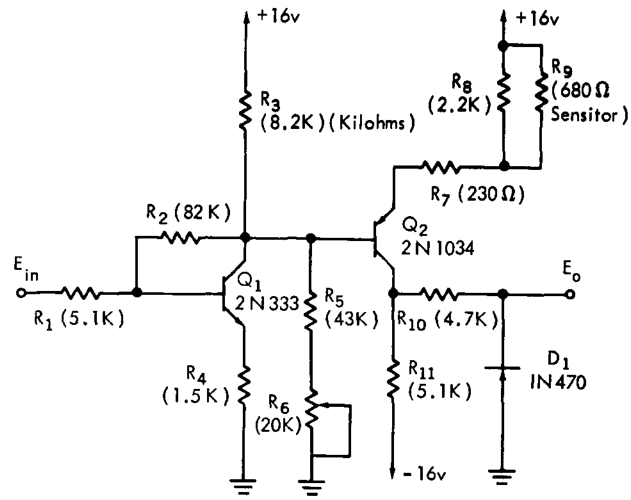

Figure 4—Final design of the two-stage amplifier.

3. For temperature compensation, select different values for R_7, R_8, and R_9 — the sum total resistance in the emitter leg to be 680 ohms.

In some applications, a 4-millisecond rise time was desirable (actually, a reduction in rise time). To achieve this, the zener diode D_1 was removed and replaced with a 0.1-microfarad capacitor. With the diode removed, the voltage, under saturated conditions, can rise to about 10 volts. Although this was beyond the original allowable input voltage of the telemetry transmitter, it did not have any adverse effects.

TESTING, FABRICATION, AND PACKAGING

The 10-gain amplifier was temperature cycled in an oven, with sufficient time allowed for temperature stabilization at each data point. The 10-gain and the electrometer amplifiers were cycled under the same conditions — the end results being, in both cases, within the required specifications.

Curves were obtained on the 10-gain amplifier for the output voltage versus input voltage at different temperature levels. Also, curves were obtained on the electrometer amplifier and the 10-gain amplifier connected together for a current input range from 10^{-7} to 10^{-9} ampere — plotting the output voltage from the electrometer and the 10-gain amplifier versus the current input at different temperature levels.

Figure 5 presents a dc gain calibration curve of the 10-gain amplifier operating with the electrometer amplifier for a current input to the electrometer amplifier of 10^{-9} ampere.

The rise time of the unit was checked and adjusted, utilizing a photomultiplier tube and a segmented rotating chopper between a light source and the tube.

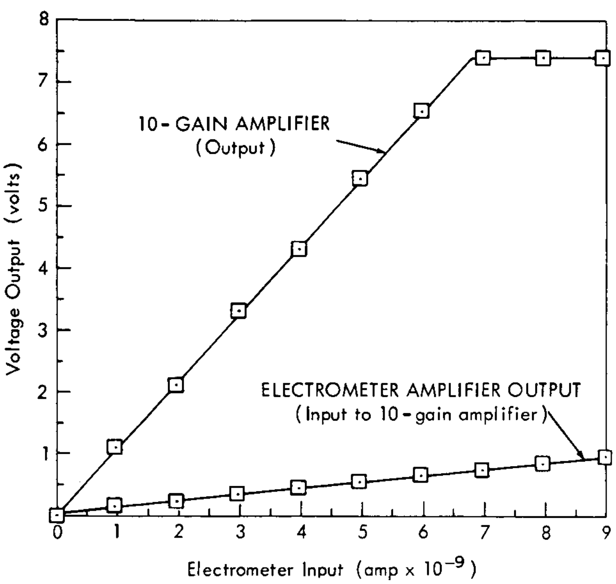

Figure 5—Direct-current gain calibration curve.

The 10-gain amplifier and the electrometer amplifier were constructed on a 1/16-inch-thick glass epoxy board measuring approximately 4 by 3 1/4 inches. Printed circuit techniques were utilized. Components were rigidly mounted on the board and were later coated with epoxy for resistance to atmospheric effects and high-G vibrational loading.

The amplifiers were packaged in a metallic can and inserted into an amplifier rack which acted as a heat sink and RF shield. The total temperature rise on the amplifier boards during an actual 6-minute rocket flight was +2 °C.

Figure 6 shows a photograph of an assembled electrometer and 10-gain amplifier. Four of these units were first flown on an Aerobee 150A, NASA 4.11 to an altitude of 107 miles from Wallops Island, Virginia, on November 22, 1960.

CONCLUDING REMARKS

These amplifiers have performed satisfactorily in several Aerobee rocket flights in conjunction with an electrometer amplifier as the basic means of extending the dynamic range within the constraints imposed by the telemetry and the desire to obtain a linear measure of ultraviolet star intensity with constant accuracy.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the work of my colleagues, W. Freeman and W. A. Gallo, Jr., who performed the laboratory work so necessary in arriving at a finalized design that successfully met all the system requirements.

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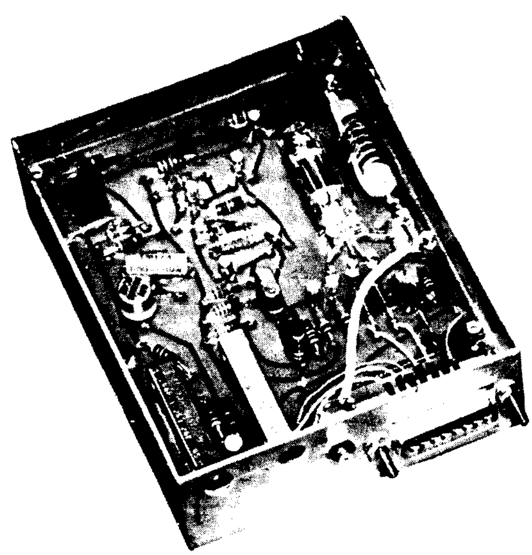

Figure 6—Packaged electrometer and 10-gain amplifier.

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